

Hybrid wireless hull monitoring system for naval combat vessels

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There is increasing interest by the naval engineering community in permanent monitoring systems that can monitor the structural behaviour of ships during their operation at sea. This study seeks to reduce the cost and installation complexity of hull monitoring systems by introducing wireless sensors into their architectural designs. Wireless sensor networks also provide other advantages over their cable-based counterparts such as adaptability, redundancy, and weight savings. While wireless sensors can enhance functionality and reduce cost, the compartmentalised layout of most ships requires some wired networking to communicate data globally throughout the ship. In this study, 20 wireless sensing nodes are connected to a ship-wide fibre-optic data network to serve as a hybrid wireless hull monitoring system on a high-speed littoral combat vessel (FSF-1 Sea Fighter). The wireless hull monitoring system is used to collect acceleration and strain data during unattended operation during a one-month period at sea. The key findings of this study include that wireless sensors can be effectively used for reliable and accurate hull monitoring. Furthermore, the fact that they are low-cost can lead to higher sensor densities in a hull monitoring system thereby allowing properties, such as hull mode shapes, to be accurately calculated.

Keywords: naval vessels; structural monitoring; hull monitoring; wireless sensor networks

1. Introduction

The US Navy is currently exploring novel ship design concepts optimally suited for future littoral combat operations. For example, the joint high-speed vessel (JHSV) and littoral combat ship (LCS) acquisition programs are focused on high-speed ships constructed from lightweight materials such as aluminium alloys (Hess 2007). In addition to the use of new materials, many of the vessels under investigation in the JHSV and LCS acquisition programs employ non-conventional hull forms including the use of multi-hull catamarans. The combination of lightweight aluminium and multi-hull forms provide ships with the speed and manoeuvrability necessary for littoral combat operations. However, high-performance aluminium ships also provide a number of operational challenges to the naval engineering community. First, the use of aluminium in the construction of the hull will lead to higher incidences of fatigue cracking (Donald 2007); in addition, once fatigue cracks initiate, their growth in aluminium will be significantly greater than those in steel hulls. Other challenges associated with aluminium materials are stress-corrosion cracking and material

sensitisation during high operational temperatures (Katsas *et al.* 2007). Second, multi-hull ship designs can lead to complex dynamic behaviour during high-speed operation in demanding sea conditions (Hess 2007). Furthermore, the unique design of these ships increases the probability that crews will operate them near, or even beyond, their safe operating envelopes due to the loss of ‘feel’ for the vessels’ response to seaway loads (Pran *et al.* 2002).

Historically, the hulls of US Navy ships are inspected by the crew and port engineers to ensure the hull is in a state of good health. While this approach has proven effective in the past, the method does suffer from some inherent drawbacks. First, visual inspection is labour-intensive. As the Navy continues to reduce manning on future naval vessels (Lively *et al.* 2008), the manning requirements of visual hull inspections will grow increasingly difficult to satisfy. Second, visual inspection can only observe obvious damage conditions. For example, hairline cracks with small dimensions are difficult to identify visually, even when using dye penetrants (Zoughi and Kharkovsky 2008). In the case of ships constructed of

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aluminium, thick insulation is commonly installed to protect the aluminium hull from heat and fire. Visual inspection would require removal and reinstallation of the insulation, which adds significant complexity and cost to the inspection process. The US Navy is therefore interested in the development of permanent hull monitoring systems that monitor the anticipated performance and health of high-performance aluminium vessels. This interest is in response to the maintenance issues (e.g. fatigue cracking) and inspection difficulties associated with high-speed aluminium ships.

Hull monitoring systems in use in the commercial shipping industry typically consist of foil strain gauges, accelerometers and gyroscopes installed throughout a vessel to measure the ship rigid-body motion and hull deformations due to seaway loads. Crews provided with real-time hull response data can pilot the ship in a manner that minimises overloading during extreme seaway conditions (Pran *et al.* 2002). Commercial hull monitoring systems consisting of a handful of sensors, can cost on average \$50,000 per system to purchase and install (Slaughter *et al.* 1997). A large fraction of the system cost is associated with the installation of coaxial wiring used for the communication of sensor data to the hull monitoring system central processing unit. In addition to being expensive to install, cables add weight to the vessel, which is a critical issue for vessels designed to be lightweight, such as high-speed aluminium vessels. Furthermore, wires installed in a combat vessel are vulnerable to detriments such as heat, moisture, and toxic chemicals common in harsh military operational environments (MacGillivray and Goddard 1997). For multi-hulled aluminium ships, the costs affiliated with the installation of a hull monitoring system grows higher because of the thick insulation layers covering the aluminium hull for protection from heat and fire (Sielski 2007).

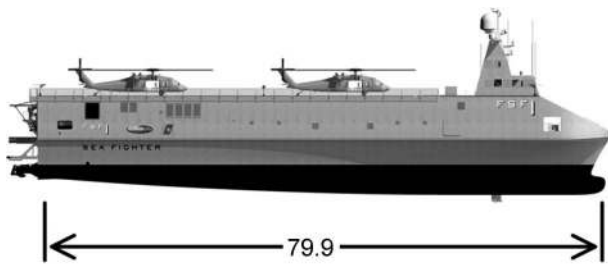
Provided the challenges associated with wired hull monitoring systems, wireless sensors can be explored for use within monitoring system architectures. Wireless sensors have emerged in recent years as low-cost alternatives to tethered sensors; their use is especially attractive for structures with large dimensions or with difficult to access spaces (Lynch and Loh 2006). In this study, a hull monitoring system is designed using wireless sensors to measure the response of a high-speed aluminium vessel undergoing sea-keeping trials. Specifically, a two-tiered hull monitoring system is proposed in the study. At the lowest layer of the system architecture, wireless sensors capable of sustaining reliable short-range communication within ship compartments are installed to collect strain and acceleration measurements of the hull. Wireless sensor networks are then connected to a shipboard fibre-optic

data network which serves as the hull monitoring system's second tier. The fibre-optic layer of the system architecture is necessary to establish communication between spatially distributed clusters of wireless sensors contained within different ship compartments. The fibre-optic network also facilitates the use of a central server to control and operate the multiple wireless sensor clusters as a single, global hull monitoring system.

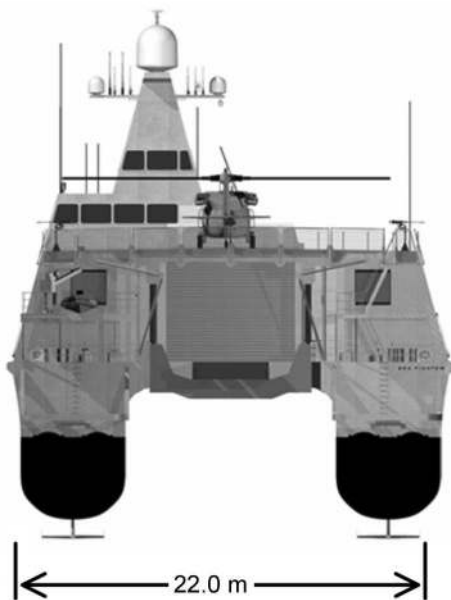
The FSF-1 Sea Fighter (Figure 1), a high-speed littoral combat vessel designed with a wave-piercing catamaran aluminium hull, is used to demonstrate the efficacy of the hybrid wireless hull monitoring system in a realistic marine environment. The strain and acceleration response of the ship is continuously and autonomously (i.e. without user intervention) collected by the hull monitoring system during a one-month transit from Panama City, Florida, to Portland, Oregon. As part of the study, a comparison between hull response data recorded by the experimental wireless hull monitoring system and those identically recorded by the ship's permanent tethered hull monitoring system is made to assess the accuracy of the experimental wireless system. Finally, acceleration hull response data collected from the wireless monitoring system is used to perform a modal analysis of the ship including identification of the ship's global modal frequencies and operational deflection shapes. First, the paper presents a detailed description of the Sea Fighter and the wired hull monitoring system installed on-board prior to this study. Then, the hybrid wireless hull monitoring system designed and installed for this study is presented in detail. The third part of the paper presents raw data collected by both hull monitoring systems along with the modal characteristics of the ship derived from the raw data presented. Finally, concluding remarks about the effectiveness of the hybrid wireless hull monitoring system in the ship-board environment are presented along with a description of the lessons learned during the study.

2. FSF-1 Sea Fighter

The FSF-1 Sea Fighter (Figure 1) is a 79.9 metres long, multi-hull catamaran-style ship designed for high-speed littoral combat missions. The ship is designed by BMT Nigel Gee (Southampton, UK) and constructed in 2003 by Nichols Brothers Boat Builders (Freeland, WA) (Bachman *et al.* 2007). To provide the ship with speed, the hull is constructed from aluminium, thereby keeping the total weight of the ship down. The Sea Fighter's hull consists of 61 identical aluminium frames evenly spaced (1.2 metres apart) along the length of the ship; six of these frames serve as watertight bulkheads. The ship is designed with three



(a)



(b)



(c)

Figure 1. The FSF-1 Sea Fighter, a high-speed aluminium ship designed to support future littoral combat operations of the US Navy: (a) side view (courtesy US Navy), (b) back view (courtesy US Navy), view of the Sea Fighter in operation (courtesy US Navy).

main levels: (1) the main deck, (2) the bridge, and (3) the machinery and tank spaces. Using both diesel and gas turbine propulsion systems, the Sea Fighter is capable of operating at speeds up to 50 knots and in conditions up to sea state 5. Sea Fighter is also equipped with a sophisticated ride control system (active rear interceptors and forward T-foils) which enhances the ship's manoeuvrability at high speed (Bachman *et al.* 2007).

Designed as a multi-purpose sea-based combat platform, the ship's main deck is relatively open for the secure housing of modular shipping containers that contain gear and equipment specific to a variety of littoral combat missions. The main deck area for storing these containers is referred to as the mission bay (Figure 2). The mission bay runs from the stern of the ship, 52 metres forward, and spans the entire width of the vessel (22.0 metres). The inside of the mission bay is generally protected from the sea environment, but does have some small openings above the ship waterline to the outside.

As Sea Fighter is an experimental vessel, the Naval Surface Warfare Center (NSWC) elected to install a permanent hull monitoring system during and after the ship's construction in 2003. The monitoring system, referred to as the scientific payload data acquisition system (SPDAS) is designed by the Technology Management Group, Inc. (TMG). In its design, the monitoring system is intended to capture data pertaining to the performance of Sea Fighter during sea-keeping trials. The SPDAS system has been in operation, collecting data on ship behaviour during operation at sea since 2006. In this study, it will serve as a baseline to which the proposed hybrid wireless hull monitoring system performance will be compared.

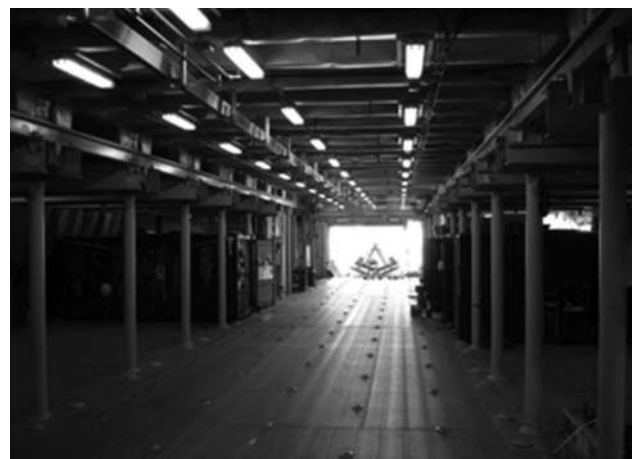


Figure 2. FSF-1 Sea Fighter mission bay. While an open space, the bay is occupied by large steel shipping containers as seen in this photograph.

2.1. SPDAS

As an experimental vessel, the Sea Fighter is closely monitored using an extensive hull monitoring system custom designed by TMG for the US Navy. The SPDAS is a wired hull monitoring system featuring 10 tri-axial accelerometers (Columbia 307-HPTX), over 100 metal-foil strain gauges (Micro Measurements), and a wave height measurement system (TSK) installed on the ship bow (Bachman *et al.* 2007). The accelerometers are intended to measure the rigid body dynamics of the ship while the strain gauges are used to measure the strain response of the hull. The TSK wave height measurement system is installed on the ship hull to measure wave height and period.

The accelerometer and strain gauges are installed throughout the ship and are interfaced to local data collection units known as data acquisition ‘bricks’. The bricks locally filter and digitise (using internal analogue-to-digital converters) the sensor data before it is communicated on the ship’s high-speed fibre-optic network. While accelerometers can be interfaced directly to the SPDAS bricks, an amplification bridge circuit is necessary to take strain measurements using metal-foil strain gauges. For this purpose, each strain gauge is connected to a Wheatstone bridge circuit (with a gain of 100) contained in an enclosure called a ‘stamp’ module. To limit load resistance, each stamp module is installed within one metre of the gauge that it services. Then, shielded coaxial wiring is used to communicate the voltage output of the stamp module to a brick where data is digitised and communicated to the server via the fibre-optic network. Measurement data communicated by the hull monitoring system’s 28 bricks are aggregated at a single data server connected to the network in a lower deck of the ship. A LabView visualisation client running on a Windows 2000 operating system is located on the ship bridge to query the server for real-time data (e.g. peak hull strain, wave height, etc.) to be presented to the crew. The system is designed to provide users with a rich set of response parameters associated with hull monitoring. The sea-keeping parameters include 6-degrees of freedom ship motion measurements, strain responses, wind and wave measurements, as well as ship control parameters.

3. Experimental setup

In this section, the prototype hybrid wireless hull monitoring system developed for the Sea Fighter is described in detail. First, the *Narada* wireless sensor platform is presented as a building block of the two-tiered hull monitoring system. Following that is a description of the hybrid wireless/fibre-optic network

developed for the system’s upper tier to aggregate data from wireless sensors installed across the ship. Finally, unattended operation of the experimental system is described in detail.

3.1. *Narada* wireless sensors

The *Narada* wireless sensor (Figure 3), developed at the University of Michigan (Swartz *et al.* 2005), is designed for use in low-cost, high-density sensor networks where the high cost of cable installation makes traditional tethered sensor networks undesirable. Furthermore, it is intended to be able to operate on battery power for a long period of time (e.g. for up to two years using a low duty cycle) in the absence of a power supply native to the monitored structure; therefore it is designed to be a very low-power device. Finally, to meet low-cost requirements, its design takes advantage of commercial, off-the-shelf (COTS) technology for all of its functional components.

The sensor node itself includes four modules (see Figure 3(a)). The first module is the computational core which is defined by the microcontroller (Atmel Atmega128) and is responsible for operation of the device. The Atmega128 is a low-power, 8-bit microcontroller with 128 kB of flash memory, 4 kB of static random access memory (SRAM), and 4 kB of electrically erasable programmable read-only memory (EEPROM). Embedded software, termed firmware, is stored within the microcontroller. The firmware includes two categories of software: first, an operating system (OS) is embedded for the configuration and operation of peripheral components on the sensor, as well as for real-time allocation of processing power. Second, application software is installed consisting of specific engineering algorithms that are responsible for local data processing of interest to the end-user. An additional 128 kB of external SRAM has also been added to the computational core in order to enhance local data buffering and computational capabilities contained within each sensor node.

The second module is the sensing interface. It consists of a Texas-Instruments ADS8341 which is a 4-channel, 16-bit analogue-to-digital converter (ADC) with an input range of 0–5 V. This interface allows the sensing system to measure data from up to four transducers per sensing node (channels numbered 0 through 3) and gives considerable flexibility in the type of transducer used. The resolution of the ADC is unique for a wireless sensing platform as it is unusually high (i.e. most commercial wireless sensors employ 10 to 12-bit ADC interfaces). *Narada* is designed with a high resolution ADC to allow for low signal data collection; low amplitude signals may be lost in the quantisation noise of the ADC if the ADC resolution

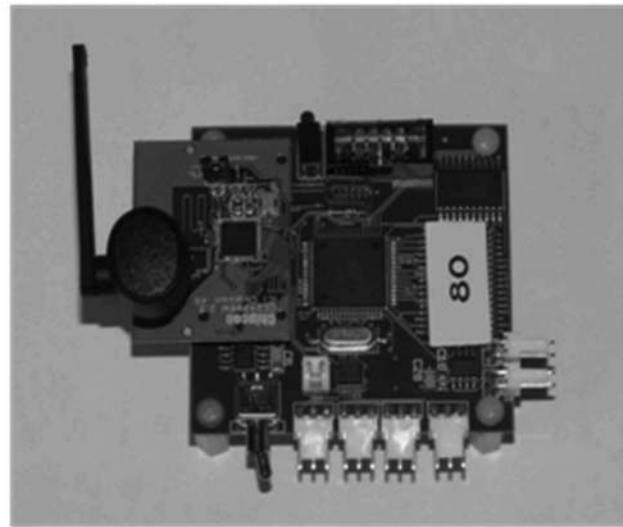
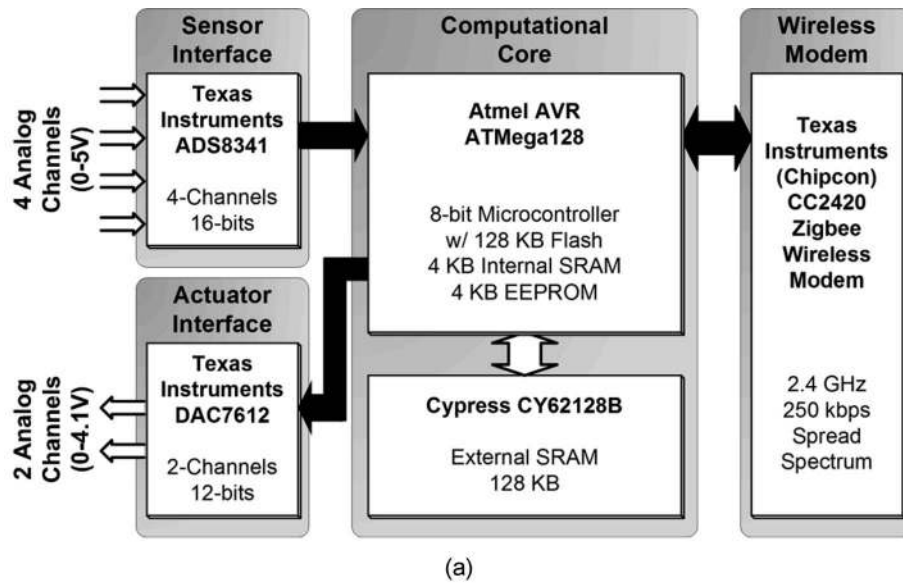


Figure 3. *Narada* wireless sensing unit: (a) architectural schematic, (b) top-view of fully assembled prototype.

is not sufficiently high. The *Narada* printed circuit board (PCB) has been carefully designed to preserve this resolution resulting in true 16-bit performance where the quantisation error is just one bit ($1/65536$ th of the input analogue voltage range, which is 5 V). The third sensor module is the actuation module consisting of a Texas Instruments DAC7612; the DAC7612 is a 2-channel, 12-bit digital-to-analogue converter (DAC) with an output range from 0 to 4.1 V. This actuation capability will not be utilised in this study.

The final module in the *Narada* design is the communication interface. The wireless interface consists of a Texas Instruments CC2420, which is a wireless transceiver that meets the IEEE 802.15.4

communications standard for dense, adaptive, and low-power wireless networking (IEEE 2006). The wireless transceiver is a spread-spectrum device that operates within the 2.4 GHz Federal Communications Commission (FCC) defined unlicensed industrial, scientific, and medical (ISM) communications frequency band. It also operates below the FCC established power limit of 1.0 W which is defined for such devices. The transceiver is capable of maintaining an over-the-air communication rate of 250 kbps and can communicate over a range of 50 metres using its native configuration. However, the range of the transceiver can be extended to up to 500 metres using a power amplified radio and directional antenna

system as has been previously developed for the *Narada* system.

The power draw of the *Narada* wireless sensor is 200 mW, assuming all components are operating simultaneously. Power savings can be accomplished by putting portions of the wireless sensor node (or the entire node) into sleep mode. The sensor is designed to run on 6 AA size nickel-metal hydride (NiMH) rechargeable batteries. Without being placed in sleep mode, the sensor would exhaust this power supply in approximately two weeks, assuming continuous operation. Because constant monitoring over a one month period is desired for this study, power is provided to the wireless sensors from the shipboard AC electrical distribution grid; Table 1 summarises the specification of the *Narada* wireless sensor.

3.2. Hybrid multi-tiered network

Due to their compartmentalised nature, naval vessels present some challenges to centralisation of measurement data from wireless sensors distributed throughout the ship. First, wireless sensors can be installed in high density because of their low costs and modular installations. However, available wireless bandwidth limits the total amount of data that can be transmitted on a given frequency channel over a given time period since only one device can transmit at a time. This fact will effectively limit the channel count that can simultaneously operate on the same wireless channel. In addition, communication reliability can be guaranteed if nodes acknowledge reception of data; this practice places greater demand on the limited wireless bandwidth.

Uncertain conditions in the wireless communication environment will also affect the reliability of the communication system (i.e. the consistency of a transmitted packet being successfully received). In the shipboard environment, three major sources of uncertainty that affect peer-to-peer communication performance, and by extension, network performance, are identified. First, changes in the usage and configuration of shipboard compartments during the voyage

may adversely change the characteristics of the communication channel. In addition, transient radio-frequency (RF) noise (e.g. from high-powered equipment on the ship) may be present and corrupt data transmissions requiring bandwidth-consuming resend protocols to be enacted. The time synchronisation between units may also be an issue since the internal clock used by each sensor may slowly drift over time. The net effect of these uncertainties is a limit to the total data that can be communicated through the network as additional time must be built into communication protocols to allow the system to recover from errors that arise due to lost packets or synchronisation errors.

In an example of the effects of these limitations, the *Narada* wireless sensor network configured to sample measurement data at 100 Hz can reliably transmit 12 to 15 channels of real-time data continuously on a single communication channel; the exact number of channels depends on the level of interference present in the wireless channel since interference requires packets to be occasionally retransmitted. To help alleviate the burden on a single communication channel, the IEEE 802.15.4 standard defines 16 communication channels within the 2.4 GHz frequency band (spanning from 2.405 to 2.485 GHz in increments of 0.005 GHz) that can be accessed simultaneously in the same space without interference with each other (IEEE 2006), thereby increasing the amount of data that may be moved through a network in a fixed space of time. By use of sub-networks (subnets) of wireless sensors on different communication channels, the achievable sensor channel count in the total monitoring system may be dramatically increased.

The second shipboard challenge, transmission of data between compartments, is more problematic for wireless sensor networks. Decks and watertight bulkheads made of conductive materials (e.g. steel or aluminium) that enclose ship compartments function naturally function as Faraday cages, reflecting virtually all incident electromagnetic waves (Harvey 1963). To overcome this inherent challenge of the shipboard environment, existing fibre-optic Ethernet network cables installed on Sea Fighter are utilised to form a wired upper tier of the hull monitoring system architecture. The fibre-optic system offers a high-data rate connection between the wireless subnets (contained in separate compartments) in the lower tier, and the data server remotely located below deck. On Sea Fighter, the SPDAS system has access points to the fibre-optic Ethernet network at the fore and aft ends of the mission bay. Access to this network provides linkage to other important areas of the ship including the SPDAS data server located below deck, the secure communications room located behind a water-tight

Table 1. Performance specifications of the *Narada* wireless sensor node.

Form Factor	6 cm × 6 cm × 2 cm
Energy Source	6 AA Ni-metal hydride batteries (7.2 V)
Power	40 mA @ 5V (max.)
Range	50 m (nominal)
Communication data rate	250 Kbps
Data acquisition sample rate	10 kHz (max.)
Cost	\$175 per unit

bulkhead on the main deck, and the bridge. A diagram depicting the multi-tier, hybrid monitoring system is presented in Figure 4.

3.3. System installation

Installation of the wireless hull monitoring system aboard the Sea Fighter takes place over four days at the Naval Surface Warfare Center, Panama City Division, in Panama City, Florida. A network consisting of 20 *Narada* wireless sensors is installed along with sensing transducers (namely accelerometers and interfaces to existing strain gauges) and receiver hardware that enables communication between the wireless sensors and a centralised data repository. These instruments are removed while the ship is in dry dock at the Cascade General Shipyard in Portland, Oregon, after two months of combined sea-keeping trials and port time.

The flexural response of the Sea Fighter is measured by the wireless hull monitoring system using

strain gauges. Strain measurements are taken from pre-existing metal-foil strain gauges (Micro Measurements) previously installed as part of the SPDAS sea-keeping system during construction of the vessel. Metal-foil strain gauges indicate changes in strain through a coupling of electrical resistance and mechanical strain (Window 1992). Changes in strain can be measured by changes in resistance but generally require power and conditioning circuitry (e.g. Wheatstone bridge and amplification) to convert the change in metal-foil resistance into a measurable analogue voltage signal. These circuits are already included in the SPDAS stamp enclosures that are installed with the strain gauges. The outputs of the SPDAS stamp enclosures located both below deck and in the superstructure above the mission bay are routed to bricks located throughout the ship. At the SPDAS bricks, analogue signals are converted into the digital domain, using on-board analogue-to-digital converters, and sent via the shipboard local area network to the data repository situated below deck. As a result, the output

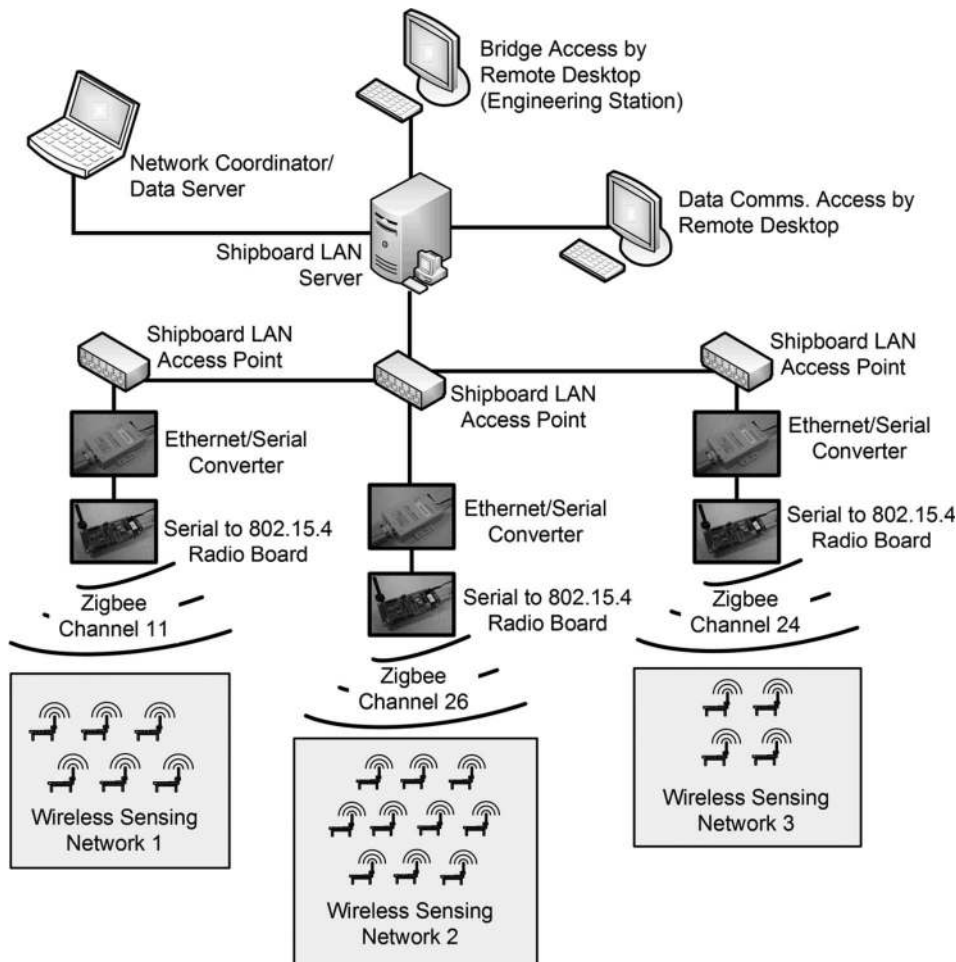


Figure 4. Overview of the multi-tiered, hybrid wireless/wired network installed on Sea Fighter.

of the wireless sensors used to record strain of the hull are installed close to the SPDAS hull monitoring system bricks where the voltage signal from the stamp

enclosures are collected. Eight strain gauge channels from Brick 19 are spliced in order to feed them into the wireless sensor nodes; for this study the selected gauges are physically located on Frame 20 (see Figures 5 and 6). The voltage output levels of the SPDAS strain channels are between 0 and 5 V which perfectly meet the input requirements for the *Narada* sensing interface. Preliminary tests of the SPDAS strain/*Narada* interface suggest some high-frequency noise contamination due to the splicing of the cable at the brick. As a result, each strain gauge sensor channel is provided with a low-pass, four-pole, Butterworth filter, each having a cut-off frequency of 25 Hz, prior to the interface with the *Narada* nodes. The filters are assembled on a solderless breadboard and installed in weatherproof enclosures with the wireless sensors (Figure 7a). Four *Narada* wireless sensor nodes are used to record the eight strain measurements; each sensor node is configured to collect two channels of strain data.

Acceleration is recorded using micro-electro-mechanical systems (MEMS) accelerometers installed throughout the mission bay (Figure 6). Vertical-only acceleration measurements are collected using Crossbow CXL02LF1Z accelerometers. The CXL02LF1Z has an input range of 0 to 2 g, a sensitivity of 1 V/g, a DC-offset of 2.5 V, an output range between 0 and 5 V, and a noise floor of 1 mg (RMS). Crossbow CXL02TG3 ultra-low noise, tri-axial accelerometer arrays are also provided along the centreline of the ship. The performance characteristics of the CXL02TG3 include an input range of 2 g, a sensitivity of 0.833 V/g, a DC-offset of 2.5 V, an output range

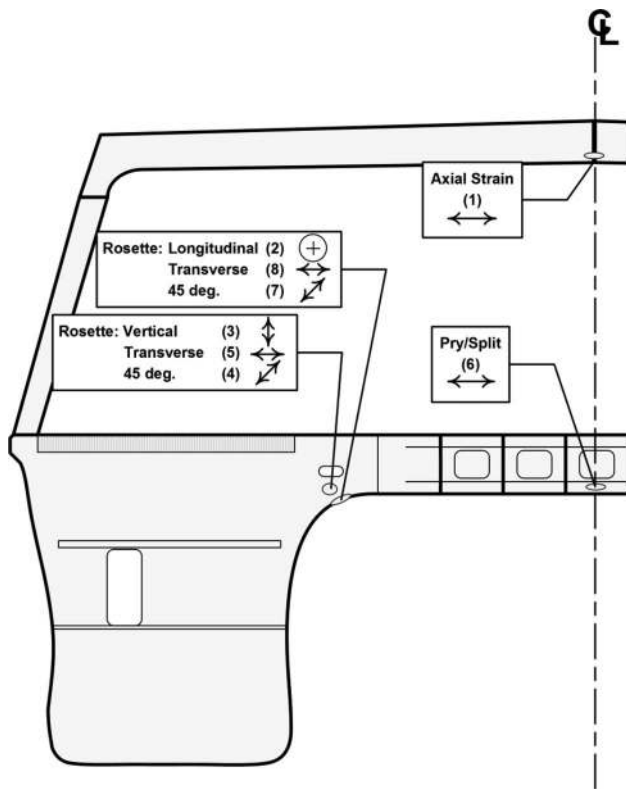


Figure 5. Layout of metal-foil strain gauges on Frame 20 measured by the proposed hybrid wireless hull monitoring system.

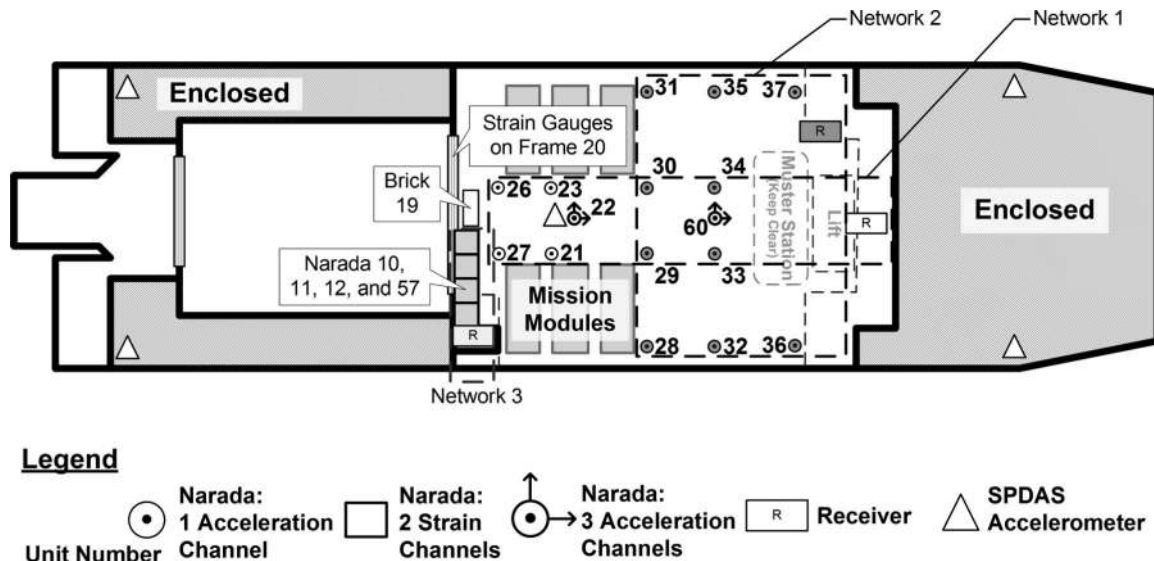


Figure 6. Layout of the wireless sensing network divided into three subnets in the Sea Fighter mission bay.

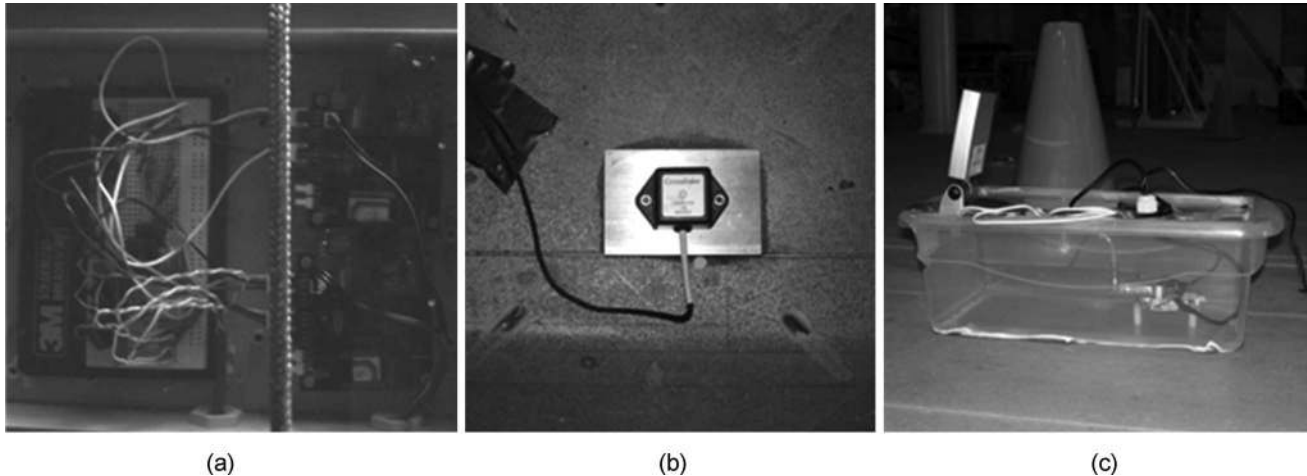


Figure 7. Details of the wireless sensor installation on Sea Fighter: (a) Four-pole Butterworth filter with Narada nodes for strain gauge de-noising, (b) accelerometer bonded to mission bay deck by epoxy, (c) wireless sensor within an enclosure with directional antenna installed in the mission bay.

between 0.5 and 4.5 V, and a noise floor of 0.6 mg (RMS). For temporary installation of accelerometers, mechanical connections such as screws are best so that the transducer is not damaged during removal. Since drilling holes for screws in the deck is deemed unacceptable, accelerometers are instead screwed to 1.2 cm thick aluminium mounting plates that are securely bonded to the deck by epoxy (Figure 7b). Protection of the accelerometers from crew activity is provided by rubber traffic cones placed over the top of the accelerometers and epoxied in place (Figure 7c). The layout of the accelerometers in a regular grid pattern is intended to generate response data for modal analysis of the ship.

A laptop computer that co-ordinates sea-keeping data collection runs and archives wireless sensor data is installed below deck in close proximity to the SPDAS data server. This laptop controls the wireless sensor subnets through a pair of bridge devices (Figure 4). A commercial wireless transceiver development kit (Texas Instruments CC2420DBK) is commonly used by a central data server to wirelessly communicate with the wireless sensor nodes. The development kit has a CC2420 transceiver (just like the *Narada* nodes) supported by an Atmel Atmega128 microcontroller for wireless communications. The microcontroller is connected to a serial (RS-232) port and is configured simply to pass data from the serial port to the radio. Similarly, data packets received from the wireless radio are read, reformatted, and sent out the serial port. Unfortunately, in the proposed hull monitoring system, the laptop is not collocated with the wireless sensor nodes. This requires use of the ship fibre-optic network to communicate data between the laptop and the wireless transceiver development kit. To connect

the transceiver to the Ethernet network, a commercial serial-to-Ethernet converter box (Moxa Nport DE-311) is used as a bridge. This connector is a very powerful device because its internal firmware allows it to appear to the laptop as a local serial port even though it is remotely located on the Ethernet network. Hence, the Nport device driver handles all of the networking details when establishing communication between the laptop and the transceiver. As shown in Figure 4, a total of three Nport converters are used to connect these wireless transceiver development kits to the network; each Nport/transceiver pair is packaged in a weatherproof container and installed in the mission bay.

The layout of the transducers, sensing nodes and receivers within the mission bay is depicted in Figure 6. Twenty *Narada* wireless sensing units, collecting the eight channels of strain data and 20 channels of acceleration data, are organised into three subnets operating on three different IEEE 802.15.4 communications channels (channels 11, 24, and 26). Dividing the wireless sensors into three subnets represents an efficient use of the wireless bandwidth which is critical for allowing continuous data streaming from the wireless sensor nodes during operation of the hull monitoring system. These sensing units are allocated into the three subnets based on their location within the mission bay, as well as their functionality (e.g. strain versus acceleration data collection). Subnets 1 and 2 include *Narada* sensing nodes measuring acceleration and have their receivers located forward in the mission bay. Subnet 1 contains two *Narada* sensing units collecting tri-axial acceleration near the centre of gravity of the ship. In addition, subnet 1 contains four *Narada* nodes, each collecting uni-axial

vertical acceleration. Subnet 2 contains 10 *Narada* sensing units collecting vertical acceleration from the forward part of the mission bay. As previously mentioned, subnet 3 consists of four *Narada* nodes recording two strain channels each. Because their communication distance is greater, directional patch antennas are used on sensor nodes in subnet 1 while omni-direction quarter-wave dipole antennas are sufficient for subnets 2 and 3. Subnet 3 is located aft of subnet 1 near SPDAS brick 19 with the receiver and Nport converter located nearby (see Figure 6).

3.4. Data collection

The proposed hybrid wireless hull monitoring system is set to continuously collect hull response data and operate in an autonomous mode, without human intervention. The *Narada* nodes are all set to collect data at a rate of 100 Hz. To begin data collection, a start beacon is initiated by the laptop serving as network coordinator and is broadcast from the wireless transceiver boards servicing each sensor subnet. Network synchronisation is handled through this beacon. Before the start command is transmitted, the *Narada* units are put in a wait state where their embedded microprocessors cycle through four assembly instructions waiting for the server command. Limiting the actions of the embedded OS in this way limits the discrepancy between processing times that may occur within the sensing nodes upon receipt of the beacon. This practice effectively limits the synchronisation error between nodes. The upper bound on synchronisation error in this system is defined by the sum of the difference in wireless propagation times from receiver to sensor (wireless signal path length divided by the speed of light) and the differential processing times for the beacon packet within the sensor. Differential processing times may arise from stochastic delays in the wireless transceiver or within the microcontroller (Maróti *et al.* 2004). Observations made on the differential processing times (absolute value) between units (measured using a digital oscilloscope in the laboratory) yield a distribution with an average synchronisation error of 10 μ s and peak observed value of 30 μ s. Assuming 1000 metres in differential path length (the high end of the system's communication range), the upper bound on the synchronisation error from the beacons network is less than 35 μ s. This error level is negligible when considering sampling in the low kHz range, or less.

Once the system is time synchronised, data is then buffered within the wireless sensor nodes until 30,000 samples are collected. After 300 seconds, the network co-ordinator queries the sensing units, one at a time,

and requests the data in packets of 50 data points each. Received packets are then archived in the data server. Because the timing within each *Narada* wireless node is not exact (each sensor relies on a crystal oscillator to keep time which are subject to drift thereby adding additional synchronisation error as data collection progresses) the system is configured to stop collecting data every 30 minutes so that the monitoring system can briefly re-synchronise before it re-initiates its data collection activities. Oscillators on the *Narada* wireless sensing nodes operate at 8.0 MHz and are rated to have stability of 2.0 parts per million (ppm) or better. This level of stability yields a worst-case clock drift of 9 ms during the 30 minute inter-synchronisation periods.

4. Results

Results of this study are presented in this section in three parts. First, data collected by the experimental wireless hull monitoring system is compared with data collected using the SPDAS wired hull monitoring system. Second, wireless reliability of data transmitted in the experimental system is discussed. Finally, results derived from modal analysis of the Sea Fighter are presented.

4.1. Comparison of wireless hull monitoring system to SPDAS system

Wirelessly collected data compares well to identical data collected by the SPDAS system. On the strain channels where the *Narada* system and the SPDAS record the same signal, the signals recorded and archived are nearly identical. Figures 8 and 9 show strain comparisons between the *Narada* derived strain time histories and those recorded by the SPDAS system of strain gauges 2 and 3 (as numbered in Figure 5), respectively, measuring hog/sag bending of the twin-hull structure. A slamming event (i.e. wave impact on the ship bow) is evident in Figure 9. In addition, some minor spikes are evident in the *Narada* signal in Figure 9 due to imperfect connections in the breadboard filter readings from the strain gauge channel. Vibrations and shock loadings generated at sea will affect the quality of these connections and corresponding noise levels. Even at the higher levels though, noise levels are within acceptable limits. Of the eight strain channels recorded by *Narada*, one of the strain gauges (or its associated power circuit) failed before the ship disembarked for its sea trials resulting in zero voltage levels recorded by both the SPDAS and the *Narada* systems for that channel (strain gauge 6). Also, one Butterworth low-pass filter failed during installation (strain gauge 7). Hence, during the sea

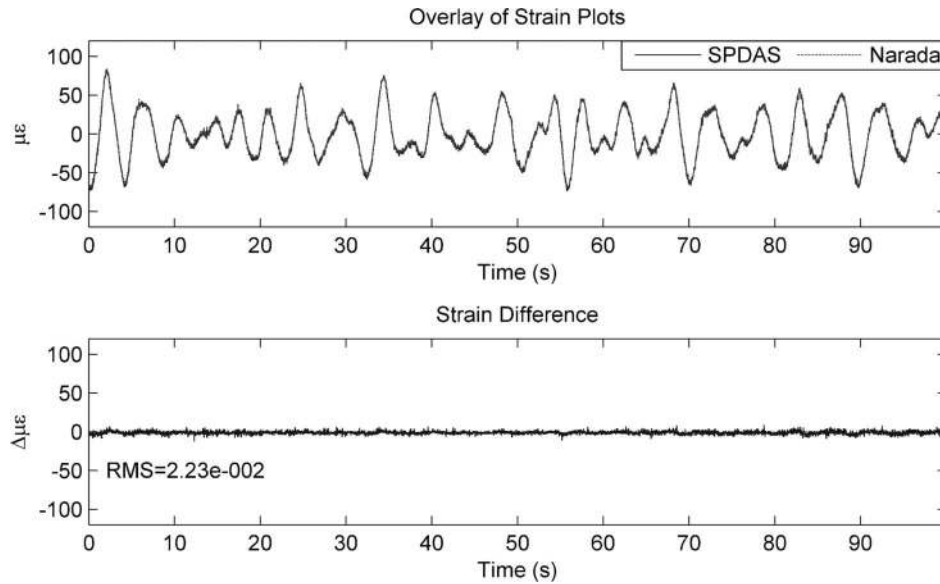


Figure 8. Time history response of the ship hull (top) during rough seas (sea state 3) as measured by the *Narada* and SPDAS based hull monitoring systems (corresponding to strain gauge 2 in Figure 5). The difference in the two measured time-histories is shown below.

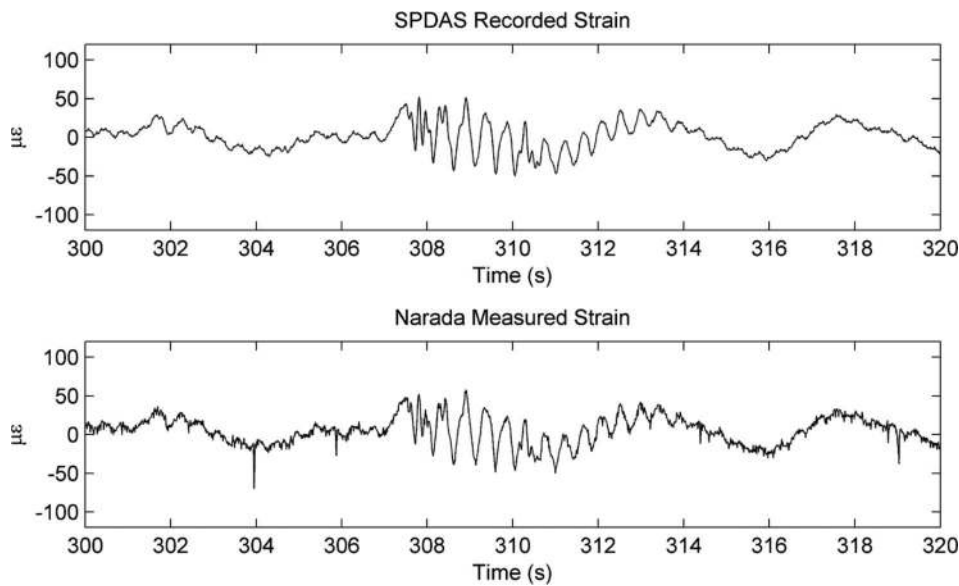


Figure 9. Strain comparison between strain measured at strain gauge 3 (in Figure 5) by the SPDAS (top) and wireless (bottom) hull monitoring systems. A slamming event is evident at 307 seconds in a transient vibration response.

keeping trials, the wireless hull monitoring system has six channels of high-quality strain measurements (strain gauges 1 to 5 and 8 in Figure 5). In general, the error between the wireless and wired strain readings is roughly less than $0.03 \mu\epsilon$, as shown in Figure 8.

The *Narada* sensing nodes recording hull acceleration do not share a channel directly with the

SPDAS hull monitoring system. However, each system does have a tri-axial accelerometer located at the ship centre-of-gravity (COG). The wireless array is located on the top surface of the mission bay deck while the SPDAS tri-axial array is mounted directly beneath, on the underside of the deck; comparison of the acceleration signals measured by these two accelerometers shows excellent agreement (Figures 10

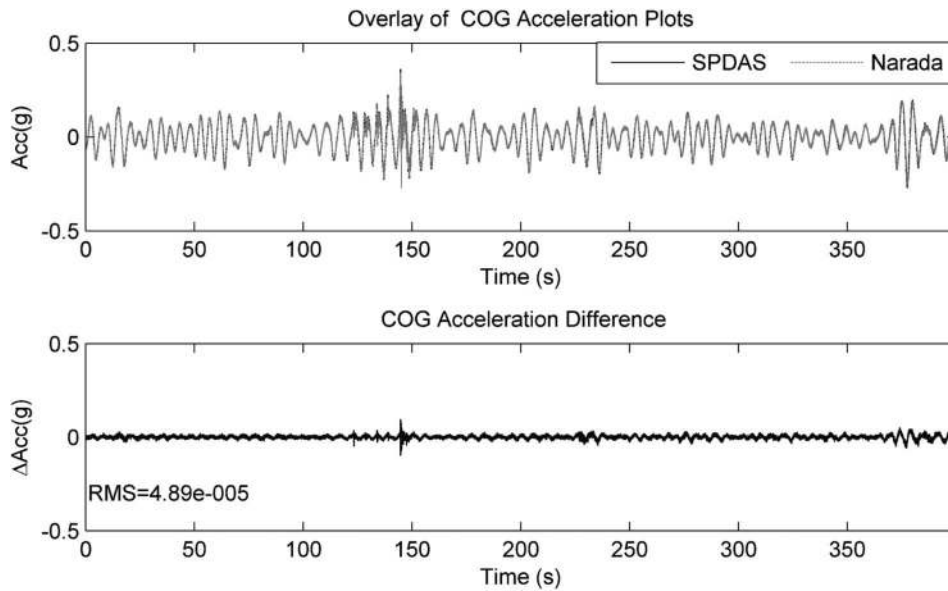


Figure 10. Comparison of *Narada* centre-of-gravity (COG) vertical acceleration measurement to that independently measured and recorded by the SPDAS system (top). The difference in measured acceleration is presented below.

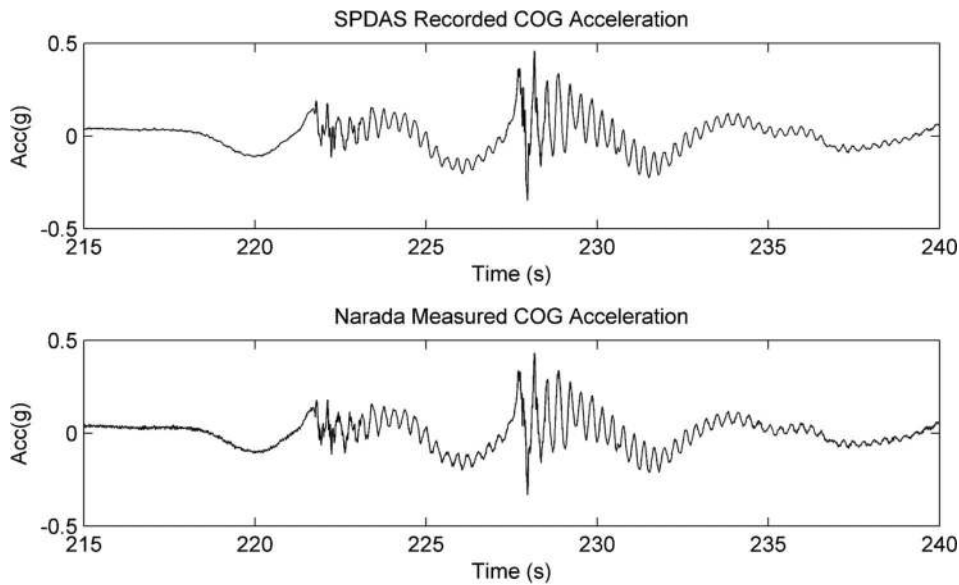


Figure 11. Centre-of-gravity (COG) response of Sea Fighter during a slamming event on the ship bow as measured by the SPDAS (top) and wireless (bottom) systems.

and 11). Both noise level and time synchronisation compare favourably between the two systems. Even in the presence of a slamming event (see the zoomed-in time history of Figure 11), the fidelity between the two systems is excellent. This result further demonstrates that the wireless sensing system can indeed operate independently of the wired monitoring system and collect high-quality data measurements.

4.2. Wireless reliability

Wireless reliability is evaluated in terms of data packets delivered to the server over the wireless communication channels, not including the effects of data loss due to timing errors brought about by contention on the wired network. Data loss is defined as data never received by the data acquisition coordinator; it does not include data lost on one transmission but successfully received

on a retransmission as part of the wireless communication resend/acknowledge protocol. In this regard, data delivery in the strain subnet (subnet 3) is very good. The communications range for all *Narada* units measuring strain is relatively constant, approximately 3 m. For these units, data loss on the wireless communication channel ranges from 0 to 3%. It is worth noting that, during early testing, units exhibited poor performance when located very close to a metal bulkhead due to their increased exposure to signal reflections. Moving them away from the bulkhead early in the voyage resulted in greatly improved reliability in subnet 3.

On the other hand, subnets made up of acceleration-based *Narada* nodes include large variability in unit communication distances, multi-path effects, and antenna configurations, leading to some very interesting results. Subnet 1, which has communication ranges as far as 30 metres, is equipped with directional, high-gain, patch antennas. The directional antennas provide robust communications as a result of increased signal strength in the direction of desired wave propagation, reduced multi-path effects, and increased clear distance between the antenna and the metal deck. While the *Narada* wireless sensing nodes have some inherent protection against adverse multi-path effects due to their use of spread-spectrum transceivers, some unacceptable performance losses due to multi-path effects were still observed during the sea keeping trials. Since these issues were only identified during the ship's voyage, the resources necessary to implement more elegant solutions (e.g. a digital data processing approach, such as blind channel equalisation, or a network approach, such as geographic routing) were not available on the ship. However, the use of directional antennas and minor modifications in antenna location proved to be quite effective as data loss on the subnet 1 wireless communication channel is between 0 and 5% during the transits under normal conditions.

Additional data loss occurs during some transient, adverse conditions. For example, if the steel doors of

the shipping containers in the mission bay are open in close proximity to a wireless sensing node (within 0.5 metres or less), the line-of-sight then between the sensing node and the receiver could be obstructed resulting in data loss as high as 50%. This result indicates that the gain in effective transmission range achieved through use of directional antennas comes at a cost of a loss in redundant wireless transmission paths. In addition, one sensing node in subnet 1 located in a very high-traffic area is damaged catastrophically very early in the transit (the node is stepped on by a crew member) and subsequently, communicates only sporadically and returns corrupted data.

Subnet 2 enjoys a shorter average distance between the receiver and sensing units than subnet 1, but sensors are equipped with omni-directional, quarter-wave dipole antennas. Sensors in this subnet exhibit both the best and worst sustained communication loss rates observed during this study. As a result of both the antennas and the geometry, data loss on the wireless channel (on average) is higher than the other two subnets due to a combination of range and multi-path interference effects. For sensors closest to the receiver, data loss is minimal, with about 0 to 1% of packets lost during the entire course of the study. For the other sensors in subnet 2 that are farthest from the receiver, data loss rate is as high as 7%. In particular, two units performed particularly poorly (these units are later replaced to test if there is some hardware malfunction with no effect). These units are physically closer to its receiver than the better performing units of subnet 1 but, due to its lower-gain, non-directed antenna, data loss is significantly higher. Other units located nearly as far from the server, but with more advantageous positioning with regards to reducing negative multi-path, give much better communications results, with only 2% data loss over the course of the study. A node by node list of wireless data delivery performance is presented in Table 2.

Table 2. Percentage data loss, by unit number, in the wireless hull monitoring network.

Unit number	Data loss (%)	Data type	Antenna type	Unit number	Data loss (%)	Data type	Antenna type
10	1	Strain	Omni	30	0	Acc.	Omni
11	1	Strain	Omni	31	2	Acc.	Omni
12	3	Strain	Omni	32	4	Acc.	Omni
21	4	Acc.	Directional	33	2	Acc.	Omni
22	1	Acc.	Directional	34	0	Acc.	Omni
23	3	Acc.	Directional	35	1	Acc.	Omni
26	5	Acc.	Directional	36	3	Acc.	Omni
27	Broken	Acc.	Directional	37	3	Acc.	Omni
28	6	Acc.	Omni	57	2	Strain	Omni
29	7	Acc.	Omni	60	0	Acc.	Directional

4.3. Operational deflection shape results

Besides simple data collection, it is desirable to use the hybrid wireless hull monitoring system for system identification of the ship, which is the first step in many structural health monitoring applications (Doebeling *et al.* 1998). Since wireless sensors have collocated memory and processing, they have the ability to process data as soon as it is collected (Straser and Kiremidjian 1998). This practice has two main advantages: it eliminates the potential glut of unprocessed data that has been collected but is never analysed, and it can alleviate bandwidth congestion if processed, low-bandwidth engineering results can be transmitted in lieu of high-bandwidth raw data. In battery powered sensor networks, this practice also saves battery power as embedded computing consumes less power than does data transmission (Lynch and Loh 2006). In this study, testing the ability of the wireless hull monitoring system to collect and archive vibrational data is of primary interest, so the modal analysis is done offline using the frequency domain decomposition (FDD) method.

This study utilises acceleration data from the wireless sensors and the FDD method to determine mode shapes from the identified modal frequencies. In the FDD method developed by Brincker, *et al.* (2001), modal frequencies are determined from the peaks of the fast Fourier transform (FFT) of the recorded output response functions. Singular value decomposition (SVD) is used to decompose the spectral density matrix at modal frequencies into single degree-of-freedom systems in the frequency domain. By decomposing the system in the frequency domain, the FDD method is very useful in determining closely spaced modes. To execute the FDD method, the power spectral density (PSD) matrix of the measured outputs, $\mathbf{G}_{yy}(j\omega)$, is necessary. The PSD matrix satisfies the input (x) and output (y) relationship:

$$\mathbf{G}_{yy}(j\omega) = \mathbf{H}^*(j\omega)\mathbf{G}_{xx}(j\omega)\mathbf{H}^T(j\omega) \quad (1)$$

where $\mathbf{G}_{xx}(j\omega)$ is the input PSD, and $\mathbf{H}(j\omega)$ is the transfer function between the known output and the unknown input. Since the input and transfer function are unknown, the following estimate of the output PSD is used instead of $\mathbf{G}_{yy}(j\omega)$ (Allemang 1999):

$$\hat{\mathbf{G}}_{yy}(j\omega_i) = F_y(j\omega_i)(F_y^*(j\omega_i))^T \quad (2)$$

where $\hat{\mathbf{G}}_{yy}(j\omega_i)$ is the estimate of the output PSD at frequency ω_i and $F_y(j\omega_i)$ is an array of FFT values of

the outputs at frequency ω_i . The next step is to determine the SVD of the output PSD matrix:

$$\hat{\mathbf{G}}_{yy}(j\omega_i) = \mathbf{U}_i\mathbf{S}_i\mathbf{U}_i^H \quad (3)$$

where \mathbf{S}_i is the diagonal matrix of singular values at frequency ω_i , and \mathbf{U}_i is the matrix of singular vectors.

$$\mathbf{U}_i = [\mathbf{u}_{i1} \quad \mathbf{u}_{i2} \quad \cdots \quad \mathbf{u}_{im}] \quad (4)$$

The singular values indicate the relative amount of energy associated with each singular vector with the most energy at that frequency associated with the first singular value. Thus, from the first singular vector, an estimate of the mode shape at that frequency may be determined.

$$\hat{\phi}_i \approx \mathbf{u}_{i1} \quad (5)$$

While the FDD method has been successfully implemented in a distributed fashion embedded on the *Narada* wireless sensor (Zimmerman *et al.* 2008), due to the complicated and unknown nature of the ship structure, the FDD method employed in this study is applied offline.

Mode shape determination from data collected aboard the Sea Fighter is particularly challenging due to the nature of the input to the system. The input is highly coloured, not broadband, and further influenced by the ship's ride control system that mitigates the effects of the sea upon the vessel rigid-body dynamics. Due to these difficulties, it cannot be stated with certainty that any frequency dependent deflection shapes identified from the data are indeed mode shapes, therefore the term operational deflection shapes will be referred to in lieu of mode shapes. However, operational deflection shapes are known to be closely connected to mode shapes. One aid in the search for operational deflection shapes that are likely to be mode shapes is the presence of slamming events. Slamming events act as impulse-like loads (i.e. broadband) that excite all of the hull's modes. This effect can be seen in two frequency spectra identified from wirelessly collected acceleration data in the presence of and in the absence of a slamming event (Figure 12). With a slamming event present, peaks in the response spectra at 2.2 Hz and 3.3 Hz are evident (Figure 12b); without those events, those peaks are extremely difficult to discern (Figure 12a).

Figure 12 also shows that, regardless of the presence or absence of slamming events, the effect of the predominant wave period dominates the response

spectra. Throughout the transit, wave periods are measured by the TSK wave height sensor at approximately 5.0 s which corresponds to the peak in the response spectra at 0.2 Hz. If the peaks at 2.2 and 3.3 Hz do represent flexure modes of the hull, they should be invariant despite changes in ship speed and wave period. Furthermore, if the peak at 0.2 Hz is due to the wave loading, it should vary with wave period.

While variance in the wave period at 0.2 Hz is relatively small, there is some variance over the course of the transit. There is, however, almost no variance in the resonant frequencies near 2.2 and 3.3 Hz. The location of the dominant peak in the frequency spectrum (near 0.2 Hz), on the other hand is variable, and strongly correlated to the wave period and ship speed. Specifically, that period is correlated to wave period and the inverse of ship speed. The correlation between spectra peak period and wave period is plotted in Figure 13. The linear regression between the wave period and main peak period is almost one-to-one (slope = 1.0366) while it is nearly uncorrelated (slope = -0.0041 and slope = 0.0002, respectively) for the 2.2 and 3.3 Hz peaks.

As shown in Figure 14, the two operational deflection shapes calculated using FDD at 2.2 and 3.3 Hz correspond to torsion and hog-sag modes of the ship, respectively. It should be noted that the accelerometers interfaced to the wireless hull monitoring system correspond to the central section of the ship. However, the SPDAS hull monitoring system has accelerometers at the four corners of the ship, as well as at the centre of gravity, which would provide a more comprehensive view of the global operational deflection shape. The operational deflection shapes obtained by applying FDD to the combined acceleration measurements from the experimental hybrid wireless system and the SPDAS hull monitoring system (time synchronised in post-processing using the COG acceleration measurement as a reference) are shown in Figure 15. The two operational deflection shapes obtained from the combined data set help to confirm the findings obtained by the wireless hull monitoring system alone.

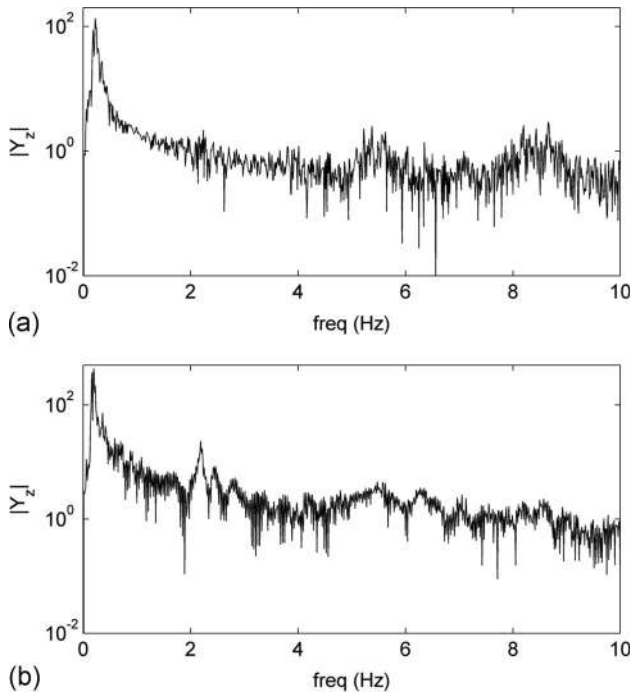


Figure 12. Response spectra of the Sea Fighter measured at accelerometer location 35 (in Figure 7): (a) Without slamming event, (b) with slamming event.

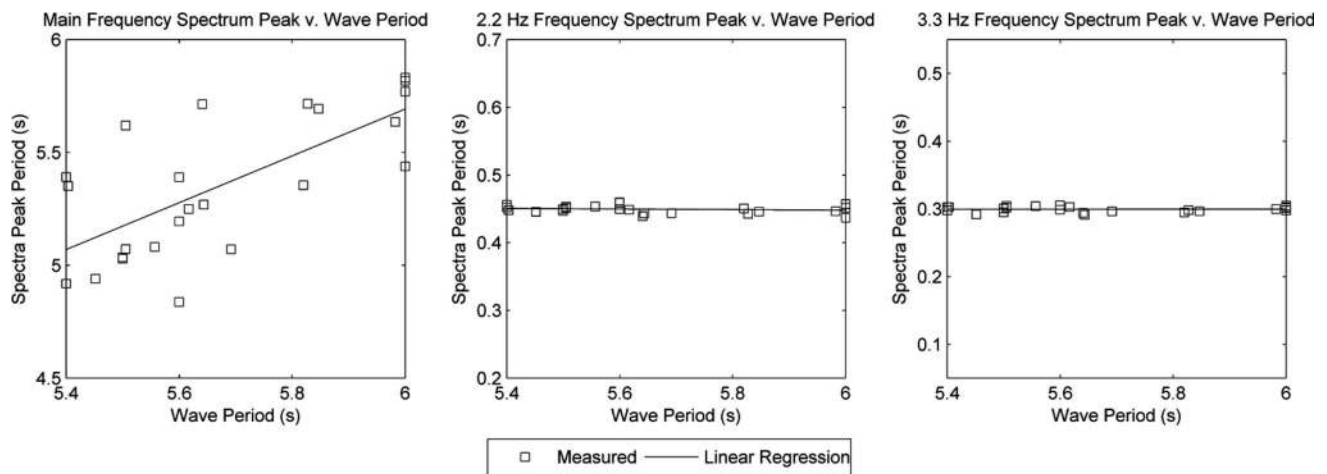


Figure 13. Correlation of identified spectra peak period to wave period using data collected during the transit between Long Beach and San Francisco.

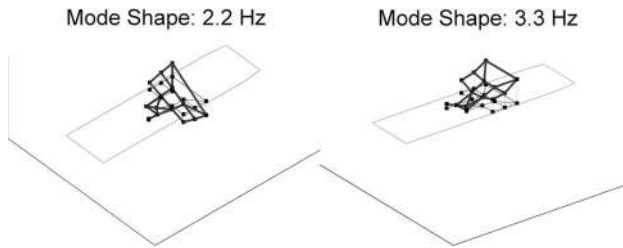


Figure 14. Operational deflection shapes determined from *Narada* collected acceleration data.

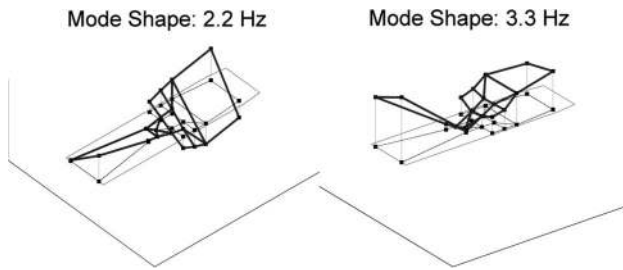


Figure 15. Operational deflection shapes determined from combined *Narada* and SPDAS collected acceleration data.

5. Conclusions

For this study a wireless sensing network is installed and tested on the FSF-1 Sea Fighter during transit from Panama City, Florida, to Portland, Oregon. The system is based on the *Narada* wireless sensor, a wireless sensing platform developed specifically for vibrational monitoring. Twenty *Narada* sensors recording 28 channels of strain and acceleration data are installed on three subnets in the Sea Fighter mission bay. These sensors communicate with receiver boxes that are interfaced with the existing shipboard Ethernet network via serial-Ethernet converters that abstract the networking details from the network coordinator. The network co-ordinator server is below deck and is accessed via remote desktop from the ship's secure communications room as well as from the bridge. This experimental validation of a hybrid sensing network composed of wired and wireless tiers demonstrates the value of combining the strengths of both technologies in a single system. Wireless sensors are used to collect hull response data from transducers located throughout a ship's compartment. Once consolidated at a receiver box, a high-bandwidth wired system carries the sensor data through bulkheads to a central repository below deck.

Once collected, wirelessly collected data compares well with data collected by the wired system. Comparisons between the strain signals recorded by the SPDAS monitoring system and the proposed hybrid wireless hull monitoring system show little difference

between the two. Errors observed are, on average, in the range of 0.023 micro-strain, RMS. In these cases, the SPDAS and the proposed wireless hull monitoring systems share use of the same transducers. Comparisons of acceleration data between the SPDAS and the proposed wireless hull monitoring systems (each collecting data measured from independent transducers) also show very good agreement, with representative errors less than 50 μg , RMS. These results demonstrate the high-fidelity of the hybrid wireless hull monitoring systems.

Data is transmitted successfully with little data loss due to use of a robust send/acknowledgement protocol when wirelessly communicating. The reliability results obtained in this study demonstrate that high quality wireless communications can be achieved in the shipboard environment, but a number of factors influence success and can greatly impact the quality of the wireless communication system. The most critical component in most wireless applications is transmission power (strongly correlated to range), but in many shipboard applications, compartments are small enough that range is not a factor. However, the mission bay, which is nearly 60 metres long, is an exception. Just as important as range on Sea Fighter (and likely more important on vessels lacking large, open bays) are multi-path effects. Multi-path effects can be harmful as well as helpful. They are harmful when primary and secondary transmission waves reach a receiver antenna simultaneously, resulting in decoding errors by the wireless receiver. Negative multi-path effects are significantly alleviated on subnet 1 by use of directional antennas. However, some of the useful aspects of multi-path effects are mitigated as well including the provision of redundant signal paths that can overcome transient conditions such as physical obstructions along the primary line-of-sight pathway between transmitter and receiver. Wireless sensors located near their receivers or those that used directional antennas performed extremely well in the sea trials. Sensors relatively far from receivers using omni-directional antennas did not perform as well, suggesting that wireless communication issues arose as a result of a combination of range and multi-path effects. Greater use of directional and high-gain antennas (where appropriate) and power amplified radios will improve performance where data loss is an issue. Creating clear space, wherever possible, between decks (or bulkheads) and the antennas attached to the *Narada* nodes, will also help in improving the reliability of the wireless channel. As such, this study identifies sensing node placement, receiver placement, and antenna selection as non-trivial tasks in shipboard installations. In addition, the application of advanced wireless signal processing and routing algorithms to

alleviate negative multi-path effects promises to be a very fruitful avenue for future investigation in the area of wireless sensing in compartmentalised metal structures such as the Sea Fighter.

Improvements in the communications performance can be accomplished by taking advantage of additional board features and additional testing. One feature of the CC2420 wireless modem employed by the *Narada* wireless sensor is that it returns to the microcontroller a measurement of the received wireless signal strength whenever it decodes a packet. This information can be used to provide to the network a real-time map of network reliability given transient conditions. This information can be used at the time of installation to optimise sensor node location and antenna orientation for maximum performance. Second, leveraging the computational abilities of the sensor for embedded data processing can greatly improve robustness and reliability of the wireless communication channels as well as save battery power (where necessary) as data transmission is an energy intensive operation for the wireless unit (Lynch *et al.* 2004). Communication of raw data over the wireless communication channels consumes a large amount of bandwidth and is a practice that scales poorly as sensor networks grow in size. Communicating a reduced set of processed data alleviates stress on the available bandwidth, thereby increasing the time window available for multiple, robust resend/acknowledge protocols to help ensure that data is delivered.

Future work should include even larger sensor networks, defined by hundreds of sensor channels with both greater physical resolution and scope (i.e. a denser sensor network located throughout the entire length of the ship). Greater reliance on embedded data processing will alleviate demand on the crowded wireless communication band, increase system scalability, and reduce the system's reliance on the data servers that serve as potential single points of failure. The use of wirelessly collected acceleration data for modal analysis of the ship demonstrates the value of the hull response data. Leveraging the ability of wireless sensors to serve as a platform for economical, high-density sensing networks can also help in making automated ship-board hull health monitoring systems a reality.

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